UPPER BOUND ON THE LIGHTEST NEUTRALINO MASS IN THE MINIMAL NON–MINIMAL SUPERSYMMETRIC STANDARD MODEL

S. Hesselbach , G. Moortgat-Pick
IPPP, University of Durham, Durham, DH1 3LE, U.K.

D. J. Miller , R. Nevzorov [a b]
Department of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, U.K.

M. Trusov
Theory Department, ITEP, Moscow, 117218, Russia

*Abstract.*We consider the neutralino sector in the Minimal Non–minimal Supersymmetric Standard Model (MNSSM). We argue that there exists a theoretical upper bound on the lightest neutralino mass in the MNSSM. An approximate solution for the mass of the lightest neutralino is obtained.

Supersymmetric (SUSY) models provide an elegant explanation for the dark matter energy density observed in the Universe. To prevent rapid proton decay in SUSY models the invariance of the Lagrangian under R–parity transformations is usually imposed. As a consequence the lightest supersymmetric particle (LSP) is absolutely stable and can play the role of dark matter. In most supersymmetric scenarios the LSP is the lightest neutralino, which provides the correct relic abundance of dark matter if it has a mass of $\mathcal{O}(100\text{ GeV})$.

In this article we explore the neutralino sector in the framework of the simplest extension of the minimal SUSY model (MSSM) — the Minimal Non–minimal Supersymmetric Standard Model (MNSSM). The superpotential of the MNSSM can be written as follows [1–3]

$$W_{MNSSM} = \lambda \hat{S}(\hat{H}_d \epsilon \hat{H}_u) + \xi \hat{S} + W_{MSSM}(\mu = 0)\,, \tag{1}$$

where $W_{MSSM}(\mu = 0)$ is the superpotential of the MSSM without μ-term. The superpotential (1) does not contain any bilinear terms avoiding the μ–problem. At the same time quadratically divergent tadpole contributions can be suppressed in the considered model so that $\xi \leq (\text{TeV})^2$ [1,2]. At the electroweak (EW) scale the superfield $\hat{S}$ gets a non–zero vacuum expectation value ($\langle S \rangle = s/\sqrt{2}$) and an effective μ-term ($\mu_{eff} = \lambda s/\sqrt{2}$) is automatically generated.

The neutralino sector of the MNSSM is formed by the superpartners of the neutral gauge and Higgs bosons. In the field basis ($\tilde{B}$, $\tilde{W}_3$, $\tilde{H}_d^0$, $\tilde{H}_u^0$, $\tilde{S}$) the

[a]On leave of absence from the Theory Department, ITEP, Moscow, Russia.
[b]e-mail: r.nevzorov@physics.gla.ac.uk

neutralino mass matrix reads

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c_\beta & M_Z s_W s_\beta & 0 \\ 0 & M_2 & M_Z c_W c_\beta & -M_Z c_W s_\beta & 0 \\ -M_Z s_W c_\beta & M_Z c_W c_\beta & 0 & -\mu_{eff} & -\dfrac{\lambda v}{\sqrt{2}} s_\beta \\ M_Z s_W s_\beta & -M_Z c_W s_\beta & -\mu_{eff} & 0 & -\dfrac{\lambda v}{\sqrt{2}} c_\beta \\ 0 & 0 & -\dfrac{\lambda v}{\sqrt{2}} s_\beta & -\dfrac{\lambda v}{\sqrt{2}} c_\beta & 0 \end{pmatrix}, \qquad (2)$$

where M_1 and M_2 are the $U(1)_Y$ and $SU(2)$ gaugino masses while $s_W = \sin\theta_W$, $c_W = \cos\theta_W$, $s_\beta = \sin\beta$, $c_\beta = \cos\beta$ and $\mu_{eff} = \lambda s/\sqrt{2}$. Here we introduce $\tan\beta = v_2/v_1$ and $v = \sqrt{v_1^2 + v_2^2} = 246\,\text{GeV}$, where v_1 and v_2 are the vacuum expectation values of the Higgs doublets fields H_d and H_u, respectively. From Eq.(2) one can easily see that the neutralino spectrum in the MNSSM may be parametrised in terms of

$$\lambda\,, \qquad \mu_{eff}\,, \qquad \tan\beta\,, \qquad M_1\,, \qquad M_2\,. \qquad (3)$$

In supergravity models with uniform gaugino masses at the Grand Unification scale the renormalisation group flow yields a relationship between M_1 and M_2 at the EW scale, i.e. $M_1 \simeq 0.5 M_2$. The chargino masses in the MNSSM are also defined by the mass parameters M_2 and μ_{eff}. LEP searches for SUSY particles set a lower limit on the chargino masses of about 100 GeV restricting the allowed interval of $|M_2|$ and $|\mu_{eff}|$ above $90 - 100\,\text{GeV}$.

In contrast with the MSSM the allowed range of the mass of the lightest neutralino in the MNSSM is limited. In Fig. 1 we plot the lightest neutralino mass $|m_{\chi_1^0}|$ in the MSSM and MNSSM as a function of M_2 for different values of μ_{eff}. From Fig. 1 it becomes clear that the absolute value of the mass of the lightest neutralino in the MSSM grows when $|M_2|$ and $|\mu_{eff}|$ increase while in the MNSSM the maximum value of $|m_{\chi_1^0}|$ reduces with increasing $|M_2|$ and $|\mu_{eff}|$. In order to find the upper bound on $|m_{\chi_1^0}|$ it is convenient to consider the matrix $M_{\tilde{\chi}^0} M_{\tilde{\chi}^0}^\dagger$ whose eigenvalues are equal to the absolute values of the neutralino masses squared. In the basis $\left(\tilde{B},\, \tilde{W}_3,\, -\tilde{H}_d^0 s_\beta + \tilde{H}_u^0 c_\beta,\, \tilde{H}_d^0 c_\beta + \tilde{H}_u^0 s_\beta,\, \tilde{S}\right)$ the bottom-right 2×2 block of $M_{\tilde{\chi}^0} M_{\tilde{\chi}^0}^\dagger$ takes the form [4]

$$\begin{pmatrix} |\mu_{eff}|^2 + \tilde{\sigma}^2 & \nu^* \mu_{eff} \\ \nu \mu_{eff}^* & |\nu|^2 \end{pmatrix}, \qquad (4)$$

where $\tilde{\sigma}^2 = M_Z^2 \cos^2 2\beta + |\nu|^2 \sin^2 2\beta$, $\nu = \lambda v/\sqrt{2}$. Since the minimal eigenvalue of any hermitian matrix is less than its smallest diagonal element the lightest

neutralino in the MNSSM is limited from above by the bottom–right diagonal entry of matrix (4), i.e. $|m_{\chi_1^0}| \le |\nu|$. At the same time since we can always choose the field basis in such a way that the 2×2 submatrix (4) becomes diagonal its minimal eigenvalue μ_0^2 also restricts the allowed interval of $|m_{\chi_1^0}|$, i.e.

$$|m_{\chi_1^0}|^2 \le \mu_0^2 = \frac{1}{2}\Biggl[|\mu_{eff}|^2 + \tilde{\sigma}^2 + |\nu|^2 - \sqrt{\biggl(|\mu_{eff}|^2 + \tilde{\sigma}^2 + |\nu|^2\biggr)^2 - 4|\nu|^2\tilde{\sigma}^2}\Biggr]. \tag{5}$$

The value of μ_0 reduces with increasing $|\mu_{eff}|$. It reaches its maximum value, i.e. $\mu_0^2 = \min\left\{\tilde{\sigma}^2,\, |\nu|^2\right\}$, when $\mu_{eff} \to 0$. Taking into account the restriction on the effective μ–term coming from LEP searches and the theoretical upper bound on the Yukawa coupling λ which is caused by the requirement of the validity of perturbation theory up to the Grand Unification scale ($\lambda < 0.7$) we find that $|m_{\chi_1^0}|$ does not exceed $80 - 85\,\text{GeV}$ at tree level [4,5].

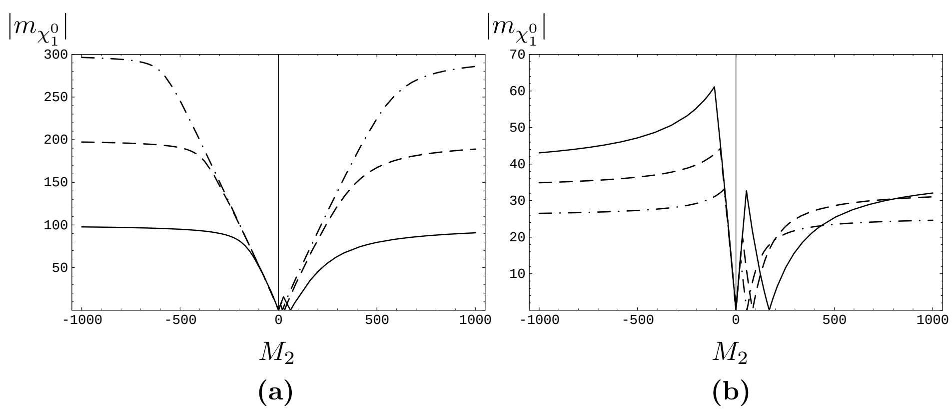

Figure 1: Lightest neutralino mass versus M_2 in the *(a)* MSSM and *(b)* MNSSM for $\tan\beta = 3$, $\lambda = 0.7$, $M_1 = 0.5M_1$. Solid, dashed and dash–dotted lines correspond to $\mu_{eff} = 100\,\text{GeV}, 200\,\text{GeV}$ and $300\,\text{GeV}$, respectively.

Here it is worth to notice that at large values of μ_{eff} the allowed interval of the lightest neutralino mass shrinks drastically. Indeed, for $|\mu_{eff}|^2 \gg M_Z^2$ we have

$$|m_{\chi_1^0}|^2 \le \frac{|\nu|^2\tilde{\sigma}^2}{\biggl(|\mu_{eff}|^2 + \tilde{\sigma}^2 + |\nu|^2\biggr)}\,. \tag{6}$$

Thus in the considered limit the lightest neutralino mass is significantly smaller than M_Z even for the appreciable values of λ at tree level.

When the mass of the lightest neutralino is small one can also obtain an approximate solution for $m_{\chi_1^0}$. In general, the neutralino masses obey the characteristic equation $\det\left(M_{\tilde{\chi}^0}-\kappa I\right)=0$, where κ is an eigenvalue of the matrix (2). However, if $\kappa\to 0$ one can ignore all terms in this equation except the one which is linear with respect to κ and the κ–independent one which allows to solve the characteristic equation. This method can be used to calculate the mass of the lightest neutralino when M_1, M_2 and $\mu_{eff}\gg M_Z$ because then the upper bound on $|m_{\chi_1^0}|$ goes to zero. We get in this limit (see [4,5])

$$|m_{\chi_1^0}|\simeq\frac{|\mu_{eff}|\nu^2\sin 2\beta}{\mu_{eff}^2+\nu^2}\,. \tag{7}$$

According to Eq.(7) the mass of the lightest neutralino is inversely proportional to μ_{eff} and decreases when $\tan\beta$ grows. At small values of λ the lightest neutralino mass is proportional to λ^2 because the correct breakdown of electroweak symmetry breaking requires μ_{eff} to remain constant when λ goes to zero. At this point the approximate solution (7) improves the theoretical restriction on the lightest neutralino mass derived above because for small values of λ the upper bound (5)–(6) implies that $|m_{\chi_1^0}|\propto\lambda$. Note, however, that the lightest neutralino is predominantly singlino if M_1, M_2 and $\mu_{eff}\gg M_Z$ which makes its direct observation at future colliders quite challenging.

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